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EFFECTS OF FAST NEUTRONS ON
POLYCRYSTALLINE ALUMINA AND OTHER
ELECTRICAL INSULATORS AT TEMPERATURES
FROM 60° TO 1230°C

G. W. Keilholtz
R. E. Moore
H. E. Robertson

OAK RIDGE NATIONAL LABORATORY
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ABSTRACT

The effects of fast neutrons on four commercial polycrystalline alumina products of high density were investigated. These materials have been considered for use as electrical insulators in nuclear-powered thermionic converters. Fast-neutron fluences up to 5.8×10^{21} neutrons/cm² (> 1 MeV) were achieved; irradiation temperatures ranged from 60 to 1230°C.

At temperatures below 100°C, there was very little damage, as is usually manifested by gross fracturing, volume increase, and separation at grain boundaries. Damage was much worse, however, at temperatures from 570°C to 1070°C, which is the range of greatest interest for thermionic applications. At about 1100°C and above, in-reactor thermal annealing was rapid enough to reduce damage significantly, but at much higher temperatures ($\sim 1230^\circ\text{C}$), damage again increased.

Based on the irradiation results, the following conclusions and recommendations were made for the use of polycrystalline alumina in thermionic converters: (1) the alumina should be of high purity to minimize gross fracturing, and it should be of small grain size to minimize the effects due to separation at grain boundaries, (2) the thermionic device should be designed for continuous operation because thermal cycling apparently promotes separation at grain boundaries, (3) the design should allow for an increase in volume of the alumina insulators of about 3%, and (4) alumina of high purity and small grain size can withstand fast neutron fluences up to about 3×10^{21} neutrons/cm² in an ETR type neutron spectrum and up to about 2×10^{21} neutrons/cm² in an EBR-II type spectrum for those neutrons with energies greater than 1 MeV.

Four other electrical insulators were investigated in a preliminary manner as possible alternatives to polycrystalline alumina for thermionic applications. These are: (1) single-crystal Al₂O₃, (2) single-crystal MgO of high purity, (3) transparent polycrystalline Y₂O₃, and (4) silicon oxynitride (Si₂ON₂). The preliminary results were very encouraging. More comprehensive investigations of these materials appear to be warranted.

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INTRODUCTION

Nuclear thermionic fuel elements must have electrical insulators as seals between the metallic emitters and collectors.¹⁻³ These insulators must be able to withstand fast-neutron bombardment at high temperatures for long periods of time since they are inside the reactor core. High-density alumina is the prime candidate for this application because its fabrication is well developed and its electrical properties are well defined. Before it can be incorporated into designs of prototypes of practical nuclear thermionic converters, however, its limits of stability toward fast neutrons at high temperatures must be defined. It is also desirable to establish the mechanisms of fast-neutron damage to alumina so that its optimum fabricational properties can be specified for thermionic application.

We have completed a program of several years duration to accomplish these objectives. Four commercial alumina products actually considered for use in prototypes of thermionic converters were selected for investigation. All four products were of high density but they differed in purity and average grain size. The program consisted of a series of irradiations over a broad range of temperature, fast-neutron flux, fast fluence and fast-neutron energy that encompassed those conditions to which the insulators would be exposed in a practical thermionic converter.

The assemblies in the series that were irradiated at high temperatures contained both solid cylinders and thin-walled cylindrical shells machined from the alumina products to determine the effect of the geometry of the specimens on neutron damage. The actual geometric form of a thermionic insulator is as a thin-walled cylindrical shell.

The results of irradiations of one of the four types of alumina at low temperatures were reported previously.⁴ This report contains results for all four types at high temperatures as well as low temperatures. The observed property changes are correlated with the fast-neutron fluences

received by the specimens because displacements, which are believed to be the main cause of damage to alumina, can be produced only by the fast-neutron component of a reactor spectrum.^a On the basis of the results, we recommend the use of alumina of high purity and small grain size. The limits of temperature and fast fluence are defined for the use of alumina in thermionic converters. Mechanisms of damage over a broad range of temperature and fast fluence are discussed.

High temperature insulators other than polycrystalline alumina were investigated in a preliminary fashion; the results are reported in a separate section.

A portion of the program was devoted to high temperature irradiations of metal-clad electrical insulators supplied by other installations, who carried out the pre-irradiation characterizations of their specimens. The results of those post-irradiation examinations that were carried out at ORNL were reported to the respective installations for their evaluation.

EXPERIMENTAL

Characteristics of Alumina Specimens

The source, density, and the average grain size of each of the four types of alumina ceramics from which the specimens were fabricated are listed in Table 1. Results of spectrographic analysis of the four materials are given in Table 2. Specimens of types II, III, and IV are white, but type I is pink. The presence of 0.1% of chromium in Type I probably accounts for its pink color.

The specimens were centerless ground to their pre-irradiation dimensions. Both the diameter and the length of each specimen were measured to within 0.1 mil both before and after irradiation to determine changes in dimensions resulting from irradiation.

^aUnless otherwise stated, all fast fluences given in this report refer to those neutrons with energies greater than 1 MeV. It is recognized, of course, that displacements are produced by fast neutrons of the spectrum with energies well below 1 MeV.

Table 1. Characteristics of Commercial Alumina Products^a

Type of Alumina	Source	Bulk Density (g/cm ³)	Average Grain Size (microns)
I, Coors AD-995	Coors Porcelain Co.	3.86	13
II, Wesgo AL-995	Western Gold and Platinum Company	3.85	23
III, GE Opaque Lucalox	General Electric Co.	3.91	6
IV, GE Translucent Lucalox	General Electric Co.	3.96	25

^aAll specimens of the same type used in the irradiation program were all of the same batch.

Table 2. Analysis of Commercial Alumina Products^a

Type of Alumina	Total Impurities (wt. %)	Major Impurities (wt. %)			
		Mg	Si	Fe	
I, Coors AD-995, 13 μ m	0.42	0.1	0.06	0.06	(Cu, 0.06) (Cr, 0.1)
II, Wesgo AL-995, 23 μ m	0.25	0.1	0.1	0.03	
III, GE Opaque Lucalox, 6 μ m	0.06	0.02	0.007	0.01	(Ni, 0.01)
IV, GE Translucent Lucalox, 25 μ m	0.14	0.08	0.02	0.003	

^aSummary of spectrographic analyses performed by C. Feldman and Anna M. Yoakum, ORNL Analytical Chemistry Division.

Each specimen was examined visually at 10X magnification before irradiation to ensure the absence of fractures or other defects. A Koll-Morgen magnifying periscope was used to examine the irradiated specimens in a hot cell.

Unirradiated specimens of each of the four types of alumina were examined metallographically at 100X and 500X magnification. No microfractures or separation at grain boundaries were observed.

Irradiation Conditions

Irradiations were carried out in both the Engineering Test Reactor (ETR) and the Experimental Breeder Reactor-II (EBR-II). The details are given in Tables 3 and 4.

Irradiations in the ETR

All of the ETR irradiations were carried out in the J-12 core position, which contained a four-hole aluminum core filler piece so that four assemblies could be irradiated simultaneously. Two types of assemblies were used in the ETR: (1) low temperature uninstrumented assemblies in which the specimen temperatures were calculated, and (2) high temperature instrumented assemblies in which the capsule temperatures were measured by thermocouples.

Low-Temperature ETR Assemblies. Aluminum cylindrical holders were bored and honed to accept centerless ground alumina specimens. They were machined externally for a close fit with an outer stainless steel containment tube. The holders were segmented into either two or three sections to facilitate disassembly in hot cells after irradiation. Each assembly consisted of a vertical array of such holders within an outer containment tube. As many as 72 1/2-in. x 1/2-in. cylindrical specimens can be irradiated in such an assembly. The outer containment tube was cooled by ETR reactor water during irradiation. Details of similar assemblies with stainless steel holders instead of aluminum specimen holders are given elsewhere.⁵

Temperatures of the specimens were calculated from the gamma heat generation rate and the thermal conductivities of the materials. The high thermal conductivity of the aluminum specimen holders permitted a rapid flow of heat from the specimens to the water-cooled outer tube. Consequently, the temperatures of all the specimens within the low temperature assemblies were below 100°C.

Table 3. Irradiation Conditions of Assemblies Containing Solid Cylinders and Thin-Walled Cylindrical Shells

Assembly ^a	Types of Specimens	Irrad. Temps. (°C)	Fast-Neutron Fluence Range (n/cm ² , >1 MeV)	Number of Thermal Cycles
			x 10 ²¹	
41-23	Solid cylinders, Type IV alumina	110-325	1.3-5.2	142
41-24	Solid cylinders, Type IV alumina	110-325	0.6-2.7	77
41-37	Solid cylinders, Type IV alumina, Si ₂ ON ₂ , MgO	70-90	1.8-5.5	129
41-44	Solid cylinders, alumina of Types I, II, III, IV	60-90	0.2-0.7	14
41-46	Solid cylinders, alumina of Types I, II, III, IV	60-90	0.9-3.0	52
41-38	Solid cylinders, alumina of types I, II, III, IV Thin-walled cylindrical shells; alumina of Types I, II, III	400-1230	0.4-3.1	61
41-39	Solid cylinders, alumina of Types I, II, III, IV Thin-walled cylindrical shells; alumina of Types I, II, III	400-1230	1.0-5.8	135
0-1	Solid cylinders; alumina of Types I, II, III Thin-walled cylindrical shells; alumina of Types I, II, III	690-750	0.4-1.3	26
0-2	Solid cylinders; alumina of Types I, II, III Thin-walled cylindrical shells; alumina of Types I, II, III	~ 800°C	-	-

Table 3, continued

Assembly ^a	Types of Specimens	Irrad. Temps. (°C)	Fast-Neutron Fluence Range (n/cm ² , >1 MeV)	Number of Thermal Cycles
			x 10 ²¹	
0-4	Advanced materials: Si ₂ ON ₂ , single-crystal MgO, transparent Y ₂ O ₃ , sapphire Al ₂ O ₃	Design: 400 & 800	0.4-0.8	22
41-45	Advanced materials: single-crystal MgO, transparent Y ₂ O ₃ , sapphire Al ₂ O ₃	60-90	0.9-2.3	36

^aAssemblies with numbers beginning with 41- were irradiated in the J-12 core position of the ETR. Assemblies with numbers beginning with 0- were irradiated in the EBR-II as follows: 0-1, row 4; 0-2, row 7; 0-4, row 8.

Table 4. Irradiation Conditions of Assemblies Containing Metal-Clad Insulators

Assembly Number and Irradiation Facility	Types of Specimens	Irrad. Temps. (°C)	Fast-Neutron Fluence Range (n/cm ² , >1 MeV)	Number of Thermal Cycles
			x 10 ²¹	
41-40 (ETR, J-12 position)	Metal-clad alumina from NASA-Lewis, Fairchild-Hiller, TECO	540- 1000	0.5-2.7	75
41-42 (ETR, J-12 position)	Metal-clad alumina from TECO, GGA	366- 860	0.5-4.0	68
0-3 (EBR-II, Row 8)	Metal-clad alumina from TECO	Design: 600 and 800	0.4-0.8	22

High-Temperature ETR Assemblies. Each of the two high temperature instrumented assemblies, 41-38 and 41-39 (see Table 3), consisted of a vertical array of 13 capsules containing a total of 58 cylindrical specimens. Three to six specimens were contained in each capsule as shown in Fig. 1. The capsule temperatures were attained by gamma heating and controlled by varying the thermal conductivity of a mixture of helium and argon that flowed up the control-gas annulus. A controller connected to one of the thermocouples varied the thermal conductivity by automatically varying the helium-to-argon ratio of the gas mixture that entered the assembly below the bottom capsule. Because of uncertainties and changes in heating rates and material properties, two additional gas lines were used to introduce either helium or argon into the control-gas stream at approximately one-third and two-thirds of the distance from the top of the assembly.

Each capsule had a unique outside diameter that determined the distance across its control-gas annulus. This distance established the controlled temperature of the capsule for any gas mixture flowing through the annulus. Most of the capsules were made of stainless steel. However, a few were made of tungsten where additional gamma heating was needed to bring the temperatures of the capsules up to their required controlled temperatures. A Fortran computer program was used to calculate the widths of control-gas annuli needed to obtain the desired specimen temperatures. Heat transfer by radiation and conduction in the radial direction was considered in this computer program.

The capsules and their sleeves were designed as individual sub-assemblies that could be separated after irradiation by sawing the outer containment tube lengthwise. The capsules were loosely pinned inside the sleeves for easy removal from the sleeves. Longitudinal grooves on the inside walls of the capsules allowed the walls to be sawed through without damaging the specimens.

Not all of the capsules of the assemblies had thermocouples. The temperatures of those capsules without thermocouples were calculated by interpolation using the measured temperatures of those capsules with thermocouples and using the appropriate gamma heat generation rates for their locations in the vertical array.

Figure 1. High Temperature ETR Irradiation Capsule.

Irradiations in the EBR-II

Assemblies 0-1 and 0-2 (Table 3) were identical in every respect but were designed for different temperatures. Each assembly was an array of five capsules in which each capsule contained one solid cylinder and one thin-walled cylindrical shell of alumina of each of Types I, II, and III. The specimens were in contact with thick-walled tungsten sleeves which served as gamma heat generators. Each capsule was kept out of contact with the outer stainless steel containment tubes of the assembly by means of pins protruding from the end caps of each capsule.

The outer tube was cooled by liquid sodium metal at about 370°C. The annulus between the tungsten sleeve of each capsule and the outer tube contained helium gas to transfer heat to the outer tube. Each tungsten sleeve had a unique outside diameter that established the distance across the helium-filled annulus. This distance established the irradiation temperature of each capsule.

Four of the capsules had a cylinder of alumina within the three thin-walled alumina shells. These cylinders were drilled to contain small solid cylinders of β -silicon carbide which served as temperature monitors. Isochronal annealing of these temperature monitors after irradiation according to the procedure of Thorne et al.⁶ established the actual temperatures of the specimens in Assembly 0-1 as ranging from 690 to 750°C.

Calculation of Neutron Fluences

Fast-neutron fluences were calculated from measurements of ^{54}Mn activity generated in iron-containing flux monitors which had been placed at intervals within the irradiation assemblies. A computer program⁷ was used to correct for power changes and shutdowns of the ETR and the EBR-II. A cross section of 65 mb for the $^{54}\text{Fe}(n,p)^{54}\text{Mn}$ reaction and a half-life of 314 days for ^{54}Mn were used in the calculations. A Watt's spectrum value of 0.692 was used for the integration of fission-neutron energy above 1 MeV.

The thermal-to-fast (> 1 MeV) flux ratio in the J-12 ETR facility ranges from ~ 2 at the low ends of the flux profile to ~ 1.5 at the point of maximum flux.⁵ The EBR-II, in contrast to the ETR, has an almost pure fast-neutron spectrum; thermal neutrons are almost completely absent in the

EBR-II. The irradiation in the EBR-II was carried out to separate out any damage effects that may be produced in the alumina by thermal neutrons. Transmutations of impurity elements by thermal neutron absorptions could, for example, cause damage by embrittling the structure. Also, an irradiation in the EBR-II was desired because its spectrum is more nearly like that in a nuclear-powered thermionic converter than is the spectrum of the ETR, which is a mixed thermal-fast spectrum.

Although the threshold of the $^{54}\text{Fe}(n,p)^{54}\text{Mn}$ reaction is well above 1 MeV, the cross section used in the calculations of fluence is that for a Watt's spectrum of fast neutrons. Our reported values for irradiations in both the ETR and the EBR-II are on the same basis, i.e., for energies greater than 1 MeV. Differences in the fast spectra of the two facilities could result, however, in differences in fast-neutron damage to a material exposed to identical reported fluences in the two reactors. Atoms can be displaced from a crystal lattice by impact of fast neutrons with energies very much less than 1 MeV. Both the number of neutrons in a given energy range and the energy itself are factors that determine the extent of displacement damage. Salmi et al.⁸ of Los Alamos have shown that the damage potential of neutrons in the EBR-II spectrum with energies less than 1 MeV is greater than that in the ETR spectrum. It is expected, therefore, that alumina ceramics would sustain greater damage in the EBR-II than in the ETR for comparable reported fast fluences with energies above 1 MeV. It is also recognized that the spectrum varies from row to row in the EBR-II.

Out-of-Reactor Control Tests

Tests were conducted out-of-reactor in which the four types of alumina were subjected to the same thermal cycling that the specimens received during irradiation of the high temperature assemblies 41-38 and 41-39. Cylindrical shells as well as solid cylinders were included in the control assemblies, which were made from the same materials as the irradiation assemblies.

Each of the 13 capsules of assemblies 41-38 and 41-39 had different temperatures, which ranged from 400 to 1230°C. No attempt was made to run out-of-reactor tests at each of the 13 temperatures, but instead tests were run at three temperatures: 600, 800, and 1100°C, which cover the range of greatest interest in the experiments.

The out-of-reactor tests were intended to duplicate the conditions of assemblies 41-38 and 41-39. They did not, however, provide a temperature differential from the centers of the specimens to their outer surfaces, which existed in the irradiated specimens because they were heated by gamma heat from the reactor. Consequently, the out-of-reactor tests did not duplicate the thermal stress within the specimens that may be important in irradiation studies as far as gross fracturing of materials is concerned.

Examinations of the specimens after conclusion of the control tests showed no gross fracturing or significant dimensional changes in any of the specimens as a result of the thermal treatment.

RESULTS OF IRRADIATIONS OF POLYCRYSTALLINE ALUMINA AT LOW TEMPERATURES IN THE ETR

Two series of irradiations at low temperatures were carried out. One series of assemblies contained only solid cylinders of alumina of Type IV. The other series consisted of two identical assemblies in which solid cylinders of all four types of alumina were irradiated.

Irradiations of Alumina of Type IV

Alumina of Type IV (Ge Translucent Lucalox, grain size 25 microns) had been irradiated previously in assemblies 41-23 and 41-24 to fast fluences of up to 5.2×10^{21} neutrons/cm².⁴ The irradiation temperatures, which had been previously reported to range from 300 to 600°C, have since been recalculated and were found to have been actually within the range 110 to 325°C instead.^b The volume changes of the specimens of these

^bThe irradiation temperature of the specimens in assemblies 41-23 and 41-24 were recalculated on the basis of new information on the heat transfer properties of the assemblies during irradiation. The original reported temperatures (300 to 600°C) were calculated on the assumption that a gas gap of a few mils would exist between the stainless steel segmented specimen holders and the water-cooled outer containment tube. The measured expansion of the specimens resulting from irradiation when combined with the thermal expansion of the segmented stainless steel holders was found to be enough to provide good contact with the water-cooled outer containment tube. Recalculated values for the specimens based on the absence of a gas gap ranged from 110 to 325°C.

assemblies are plotted in Fig. 2 together with the volume changes of specimens irradiated in assembly 41-37, which operated at considerably lower temperatures (70-90°C).^c

An increase in the irradiation temperature from the range 70 to 90°C to temperatures ranging from 110 to 325°C caused greatly increased swelling of specimens receiving fast fluences greater than 2×10^{21} neutrons/cm². The additional expansion at higher temperatures is caused primarily by separation at the grain boundaries, which begins to occur at a fast fluence of about 2.3×10^{21} neutrons/cm² and becomes very severe at 4.7×10^{21} neutrons/cm².⁴ Many of the specimens exposed to fast fluences greater than 3×10^{21} neutrons/cm² were extensively fractured.

Metallographic examinations of specimens irradiated over the lower temperature range (70 to 90°C) revealed no separation at the grain boundaries. All of the 12 specimens irradiated in this assembly were free of fractures except one, which was fractured so severely that its dimensions could not be measured after irradiation. This specimen had received a fast fluence of 4.5×10^{21} neutrons/cm².

The single crystal point at 150°C of Wilks, et al.⁹ shown in Fig. 2 is consistent with the data for polycrystalline specimens. This point was calculated from their dimensional measurements of a single crystal. The a direction and the c direction of the crystal expanded by almost the same percentage.

Irradiations of the Four Types of Alumina at Low Temperature

All four types of alumina (see Table 1) were irradiated in two identical assemblies (41-44 and 41-46) at calculated temperatures ranging from 60 to 90°C. Two assemblies were used for this phase of the investigation in order to cover the very broad range of neutron fluence

^cAssembly 41-37 had aluminum specimen holders instead of stainless steel. Since aluminum has a greater thermal conductivity and a lower gamma heating rate than stainless steel, the calculated temperatures of the specimens in assembly 41-37 (70-90°C) were much lower than those in assemblies 41-23 and 41-24.

Figure 2. Volume Increase of Alumina of Type IV (GE Translucent Lucalox) After Irradiation at Low Temperatures.

that was desired. The volume increase of the specimens calculated from dimensional changes is plotted against fast fluence in Fig. 3. None of the specimens in either assembly 41-44 or 41-46 were fractured. Four of the specimens, one of each type, that had received fast fluences near the maximum in the long-term assembly (41-46) were examined metallographically and were found to be free of any separation at the grain boundaries or transgranular fracture. Because of the absence of such microfractures, the volume increase of the specimens is derived solely from the volume expansion of the grains themselves.

The data plotted in Fig. 3 indicate no differences in volume expansion among the four types of alumina. This was expected because atomic displacements, which cause the lattice to expand during irradiation, are produced uniformly throughout a specimen. The fractional expansion of the grains and hence that of a polycrystalline specimen without microfractures, therefore, should not be a function of grain size. Also, relatively minor differences in purity should not have a significant effect on volume expansion. The curve of Fig. 3 is consistent with the curve in Fig. 2 for the specimens of Type IV alumina irradiated over the temperature range 70 to 90°C.

RESULTS OF IRRADIATIONS OF POLYCRYSTALLINE ALUMINA AT HIGH TEMPERATURES IN THE ETR AND THE EBR-II

A short-term irradiation and a long-term irradiation of solid cylinders of all four types of alumina (see Table 1) and thin-walled cylindrical shells of Types I, II, and III were carried out in the ETR at temperatures ranging from 400 to 1230°C. The two assemblies were identical in every respect. An irradiation of solid cylinders and shells of alumina of

Types I, II, and III was also carried out in the nearly pure fast flux of the EBR-II to compare results with those from the irradiations in the mixed thermal-fast flux of the ETR. The temperatures of the specimens in the assembly irradiated in the EBR-II ranged from 690 to 750°C.

Figure 3. Volume Increase of Four Commercial Types of Alumina Irradiated at Low Temperature (60-90°C) in the ETR in Two Identical Assemblies.

Irradiations in the ETR

Short-Term Irradiation. Gross damage to the solid cylindrical specimens in this assembly correlates much better with the impurity content of the specimens than with any other known variable. The results are given in Table 5. Half of the solid cylinders of the two least pure types (I and II) fractured. By comparison, all of the solid cylinders of the highest-purity types (III and IV) survived without apparent gross damage. Of the seven thin-walled cylindrical shells of each of the types I, II, and III, four of Type I, four of Type II, and three of Type III fractured as a result of irradiation. In the case of the shells also, the gross damage correlated better with the impurity content than with any other variable.

Results of metallographic examinations of selected specimens did not show a definite correlation between the degree of separation at grain boundaries and gross fracture. There is no question, however, that propagation of macrofractures can occur readily in specimens with severe grain-boundary separation. A possible example of this is seen in Fig. 4. Almost no separation at grain boundaries was found in specimens of Type III, which was also one of the two best types of alumina with respect to gross fracture. Type III is the purest type, but it also has the smallest grain size, which is probably the main reason for its resistance to separation at grain boundaries.

Volume increase of the solid specimens calculated from the equation $\Delta V/V = 2\Delta D/D + \Delta L/L$ in which D and L are the diameter and length, respectively, is plotted against fast fluence in Fig. 5. It may be expressed as

$$\Delta V/V = (\Delta V/V)_c + (\Delta V/V)_g$$

in which $(\Delta V/V)_c$ is the fractional volume expansion resulting from expansion of the crystals themselves and $(\Delta V/V)_g$ is the additional expansion contributed by separation at the grain boundaries. The line in Fig. 5 is drawn through points for specimens which had been examined metallographically and found to have little or no separation at the grain boundaries. This line represents the grain-volume increase, $(\Delta V/V)_c$, for temperatures within the range 580 to 1070°C. The point obtained from direct measurements by Wilks, et al.⁹ of a single crystal irradiated at 650°C is consistent with the line.

Table 5. Gross Damage to Solid Cylinders of Alumina Irradiated in Short-Term Assembly 41-38

Fast-Fluence Range (neutrons/cm ² , > 1 MeV)	Irradiation Temp. (°C)	Types of Specimens ^a	Gross Damage
x 10 ²¹			
0.4-0.6	400	I,II,III,IV	None
1.0-1.3	710	I,II,III,IV	None
1.4-1.7	1070	I,II,III,IV	I-small crack
1.65-1.8	910	I,II,III	I-very thin crack II-very thin crack
1.75-1.95	750	II,III,IV	II-very thin crack
2.05-2.25	630	I,II,III	I-small crack
2.25-2.4	1230	I,II,III	I-large crack
2.35-2.5	580	II,III,IV	II-crack
2.8-2.95	930	I,II,III	I-large crack
2.8-2.9	790	I,II,III	None
3.1	1100	I,II,III,IV	I-broken in half II-broken in half

^aTypes: I, Coors AD-995.

II, Wesgo AL-995.

III, GE Opaque Lucalox.

IV, GE Translucent Lucalox.

Figure 4. Type II Alumina Irradiated in Assembly 41-38 at 930°C to 2.95×10^{21} neutrons/cm² (> 1 MeV). Separation at the grain boundaries is evident. There is a thin fracture that tends to follow grain boundaries. As polished.

Figure 5. Volume Increase of Four Commercial Types of Alumina After Irradiation at High Temperatures in Short-Term Assembly 41-38.

The curves of Figs. 2 and 3 for temperatures below 100°C fall considerably below the line for the grain-volume increase of Fig. 5. An increase in the irradiation temperature from ~ 100 to 580°C, therefore, causes an increase in the grain volume. This increased expansion leads, in turn, to separation at the grain boundaries in some specimens of Types II and IV, which are the two types of alumina with the largest grain size. The four specimens that were irradiated at 1100°C to fast fluences greater than 3×10^{21} neutrons/cm² did not expand as much in volume as those irradiated at temperatures within the range 580 to 1070°C. Increased in-reactor thermal annealing of defects produced by fast neutrons probably accounts for the reduced expansion at 1100°C. Thermal annealing of alumina is apparently not significant at temperatures below about 1070°C. At 1230°C, however, greatly increased expansion of specimens of Types I and II occurred. Metallographic examination of the specimen of Type II revealed very severe separation at the grain boundaries.

Long-Term Irradiation. This assembly (41-39) was identical to the short-term assembly (41-38) in every respect, but it was irradiated for a longer period of time. Gross damage to the solid cylinders is summarized in Table 6. As in the short-term assembly, about half of the solid cylinders of the two least pure types (I and II) fractured. Four specimens of the two purest types (III and IV) fractured. Three out of 11 specimens of Type III and one out of six specimens of Type IV fractured. None of the solid specimens of Types III and IV in the short-term assembly fractured during irradiation. Gross damage to the solid cylinders of assembly 41-39 did not correlate with the fast fluence or grain-size but instead appeared to be related to the impurity content of the alumina. This was also true in short-term assembly 41-38. There was also greater damage to the cylindrical shells in the long-term assembly than to those in the short-term assembly. Of the seven shells of each type of alumina, five of Type I, three of Type II, and five of Type III were fractured.

The increase in volume of the solid specimens is plotted against fast fluence in Fig. 6. The line for the increase in grain volume for the short-term assembly (41-38) and the data at 1100°C taken from Fig. 5 are shown for comparison. Also shown in Fig. 6 are data from the irradiations in the EBR-II.

Table 6. Gross Damage to Solid Cylinders of Alumina Irradiated in Long-Term Assembly 41-39

Fast-Neutron Range (neutrons/cm ² , > 1 MeV)	Irradiation Temp. (°C)	Types of Specimens ^a	Gross Damage
x 10 ²¹			
1.0-1.3	400	I,II,III,IV	None
2.0-2.5	910	I,II,III	I,II-fractured
2.1-2.5	710	I,II,III,IV	I-fractured
2.7-3.3	1070	I,II,III,IV	I-fractured
3.5-3.9	750	II,III,IV	None
3.6-4.0	1230	I,II,III	I-fractured II,III-broken
4.1-4.4	630	I,II,III	I,II-fractured
4.5-5.0	580	II,III,IV	None
4.9-5.2	930	I,II,III	III-chipped
5.4-5.5	790	I,II,III	III-broken
5.6-5.8	1100	I,II,III,IV	I,IV-broken

^aTypes: I, Coors AD-995.

II, Wesgo AL-995.

III, GE Opaque Lucalox.

IV, GE translucent Lucalox.

Figure 6. Volume Increase of Four Commercial Types of Alumina After Irradiation at High Temperatures in Long-Term ETR Assembly 41-39 and EBR-II Assembly 0-1.

Comparisons of data for temperatures ranging from 580 to 1070°C from assemblies 41-38 and 41-39 at comparable fluences reveal a greater expansion in volume of the specimens of the long-term assembly. This additional expansion may be a result of more severe separation at the grain boundaries.

A similar effect observed in beryllium oxide was attributed to the larger number of thermal cycles that the specimens undergo in long-term irradiations.¹⁰ It was proposed that thermal cycling of beryllium oxide promotes separation at grain boundaries that are stressed by anisotropic crystal expansion, thereby causing a greater volume expansion of a polycrystalline specimen.

Irradiations of Alumina of Types I, II, and III in the EBR-II

The purpose of this irradiation was to compare damage from exposure to the nearly pure fast-neutron spectrum of the EBR-II with that in the mixed thermal-fast spectrum of the ETR. Data obtained from irradiations in the EBR-II have more relevance than data from ETR irradiations for applications in nuclear-powered thermionic converters since the electrical insulators in these devices will be exposed only to a fast neutron spectrum.

The results are given in Tables 7 and 8. The only specimens that fractured were of Type I, the least pure type. This type also fractured to the greatest extent in the assemblies irradiated at high temperatures in the ETR (41-38 and 41-39). Unlike the results from the latter assemblies, however, more of the solid cylinders fractured than shells. Metallographic examinations revealed separation at the grain boundaries of specimens of Types I and II irradiated to the highest fluence (1.3×10^{21} neutrons/cm²) of the irradiation. A specimen of Type III irradiated in the same capsule did not exhibit separation at the grain boundaries.

The increase in volume of the specimens plotted in Fig. 6 indicate that there is greater damage to specimens irradiated in the EBR-II than in the ETR for measured fast fluences greater than 1 MeV. This phenomenon is discussed in the experimental section. We attribute it to a greater damage potential of the EBR-II spectrum for measured fluences in both the EBR-II and the ETR of neutrons with energies greater than 1 MeV. A better comparison of damage to alumina irradiated in different reactors would result from using fast fluences for neutrons with energies greater

Table 7. Results of Examinations of Solid Cylinders of Alumina Irradiated in the EBR-II (0-1)

Type of Alumina ^a	Fast-Neutron Fluence (neutrons/cm ² , > 1 MeV)	Irrad. Temp. ^b (°C)	Volume Increase ^c (%)	Gross Damage	Results of Metallographic Examinations ^d
	x 10 ²¹				
I	0.6	690	1.7		
II	0.7	690	2.0		
III	0.7	690	2.1		N
I	1.1	730	2.9	Fractured	
II	1.1	730	4.3		
III	1.2	730	2.7		
I	1.3	750	4.1	Fractured	G (some)
II	1.3	750	5.2		G (severe)
III	1.3	750	2.8		N
I	1.2	730	3.4	Fractured	
II	1.2	730	4.4		
III	1.1	730	2.6		N
I	1.0	690	1.6		
II	0.9	690	1.6		
III	0.9	690	1.7		

- a. I = Coors AD-995; II = Wesgo AL-995; III = GE Opaque Lucalox.
- b. Interpolated values from a plot of position in the reactor core versus temperature determined from silicon carbide temperature monitors.
- c. Calculated from measurements of the length (L) and the diameter (D) of the specimens using the equation $\Delta V/V = 2\Delta D/D + \Delta L/L$ for the fractional volume increase.
- d. N = no grain-boundary separation.
G = grain-boundary separation present.

Table 8. Results of Examinations of Thin-Walled Cylindrical Shells of Alumina Irradiated in the EBR-II (0-1)

Type of Alumina ^a	Fast-Neutron Fluence (n/cm ² , > 1 MeV)	Irrad. Temp. (°C) ^b	Volume Increase ^c (%)	Gross Damage
	x 10 ²¹			
I	0.45	670	1.2	Fractured
II	0.5	670	1.2	
III	0.6	670	1.7	
I	0.9	710	2.0	
II	1.0	710	2.8	
III	1.1	710	2.8	
I	1.2	750	2.8	
II	1.2	750	4.0	
III	1.2	750	2.5	
I	1.2	740	2.8	
II	1.2	740	4.2	
III	1.2	740	2.4	
I	1.1	710	1.9	
II	1.1	710	2.4	
III	1.0	710	2.0	

- a. I = Coors AD-995; II = Wesgo AL-995; III = GE Opaque Lucalox.
b. Interpolated values from a plot of position in the reactor core versus temperature determined from silicon carbide temperature monitors.
c. Calculated from measurements of the length (L) and the diameter (D) of the specimens using the equation $\Delta V/V = 2\Delta D/D + \Delta L/L$ for the fractional volume increase.

than 0.1 MeV rather than 1 MeV. Multiplying fluences for energies greater than 1 MeV received by specimens of alumina irradiated in the core of the EBR-II by a factor of two provides an approximate comparison with data for specimens irradiated in the ETR core.¹¹

RESULTS OF METALLOGRAPHIC EXAMINATIONS OF IRRADIATED POLYCRYSTALLINE ALUMINA

Appendix B contains photomicrographs in the as-polished condition of selected irradiated specimens from the various assemblies. Black areas seen in these photomicrographs are areas where grains had been pulled out during polishing. Pullout of grains occurs in specimens in which there is separation at the grain boundaries, or in some cases, in which the grain boundaries have been weakened by stresses caused by anisotropic expansion.

The very small white areas which can be seen in some of the photomicrographs may be silicon metal. White areas in photomicrographs of ceramic materials usually represent metallic inclusions. Silicon is produced in aluminum-containing materials by slow-neutron absorptions. The amount of the inclusion seen in Fig. 4, as an example, is no more than 0.25% of the total volume of the specimen. This small quantity of silicon is not large enough to affect the volume expansion significantly.

RESULTS OF X-RAY DIFFRACTION EXAMINATIONS OF IRRADIATED POLYCRYSTALLINE ALUMINA

X-ray diffraction examinations were carried out on selected specimens that had been irradiated at various temperatures. The X-ray patterns were diffuse, and this made it difficult to measure the a and c parameters accurately. Within the accuracy of the measurements, no significant changes in the lattice parameters could be detected.

The substantial increase in the volume of grains of polycrystalline specimens that we have observed and the dimensional increases of single crystals reported by Wilks, et al.⁹ must result, therefore, almost entirely

from agglomerates of defects too large to affect the measured lattice parameters.

IRRADIATIONS OF OTHER HIGH TEMPERATURE ELECTRICAL INSULATORS

Separation at the grain boundaries limits the usefulness of polycrystalline alumina as a thermionic insulator. Thermionic converters designed for very long lifetimes which result in fast fluences greater than 3×10^{21} neutrons/cm² will require the use of electrical insulators which do not separate at grain boundaries. We investigated several advanced materials in a preliminary manner to find potential candidates for long-term applications. These materials are: (1) single-crystal Al₂O₃ (synthetic sapphire), (2) single-crystal, high-purity MgO, (3) transparent polycrystalline Y₂O₃, and (4) silicon oxynitride (Si₂ON₂).

The synthetic sapphire (Linde) is a high-purity material made by the Czochralski process. It has no grain boundaries to separate. Cylindrical specimens were machined so that the c direction was perpendicular to the cylindrical axis. Polycrystalline MgO does not separate at the grain boundaries during irradiation, but specimens of low purity undergo gross fracturing. Single-crystal MgO of high purity was investigated to determine whether it would resist gross fracturing. The single crystals were provided by the ORNL Solid State Division. Polycrystalline yttria (Y₂O₃) also does not separate at grain boundaries and it expands only very little during irradiation, but most specimens fracture. An improved yttria ceramic, which is transparent, has been made by General Electric by addition of zirconia. This material was included in the program in the hope that it would not fracture. A new ceramic, silicon oxynitride, which is made by Norton Company, Worcester, Massachusetts, has excellent high temperature properties, but its resistance to neutron irradiation had not been determined.

Twelve solid cylinders of silicon oxynitride were irradiated in Assembly 41-37 in the ETR at 70 to 90°C to fast fluences ranging from 1.6 to 5.5×10^{21} neutrons/cm². None of the specimens fractured. Release of nitrogen gas from the specimens was found to be either negligible or non-existent. Volume changes were very small. At first, there is a shrinkage, and then there is a slight expansion. The volume change ranged from -0.24% at 1.6×10^{21} neutrons/cm² to

+0.12% at 5.5×10^{21} neutrons/cm².

Solid cylinders of synthetic sapphire, single-crystal MgO, and transparent Y₂O₃ were irradiated in Assembly 41-45 in the ETR at 60 to 90°C. Fast fluences received by the specimens ranged from 0.9 to 2.3×10^{21} neutrons/cm². Specimens of polycrystalline alumina of Types I, II, and III were included in the assembly for comparison. One of the four MgO specimens and one of the six Y₂O₃ specimens broke in half. None of the specimens of polycrystalline alumina and sapphire fractured during irradiation.

Data obtained from dimensional measurements are given in Table 9. The volume increase of synthetic sapphire is very nearly the same as that of polycrystalline alumina, but the three sapphire specimens that received the highest fluences expanded more in length than in diameter. The $\underline{c}$ parameter was oriented in the direction of the length of the cylinders. The data indicate that a change from isotropic expansion to anisotropic expansion occurs with increasing fast fluence at very low temperatures as well as with increasing temperature at constant neutron fluences. Cylindrical specimens of single-crystal MgO expanded slightly more than polycrystalline MgO that we irradiated previously.¹²

The dimensional changes of Type III alumina (GE opaque Lucalox) and the four other high temperature electrical insulators irradiated in Assembly 0-4 in the EBR-II are given in Table 10. The design temperatures were 400 and 800°C.

The only specimen in Assembly 0-4 that was fractured was the specimen of silicon oxynitride that had been irradiated at 400°C to a fluence of 0.6×10^{21} neutrons/cm². The top end of this specimen was broken off.

The data obtained from Assemblies 41-37, 41-45, and 0-4 on the four advanced materials are very encouraging. A comprehensive investigation of these electrical insulators as possible alternatives to polycrystalline alumina for thermionic applications would appear to be warranted.

Table 9. Comparison of the Volume Expansion of Polycrystalline Alumina and Three Other Electrical Insulators Irradiated at 60-90°C in the ETR (41-45)

Type of Specimen ^a	Fast Fluence (n/cm ² , > 1 MeV)	Diameter Increase (%)	Length Increase (%)	Volume Increase (%)
	x 10 ²¹			
Polycrystalline Alumina-I	1.5	0.49	0.43	1.4
	1.9	0.47	0.48	1.4
	2.2	0.55	0.47	1.6
	2.3	0.51	0.58	1.6
Polycrystalline Alumina-II	0.9	0.40	0.55	1.4
	1.4	0.45	0.52	1.4
	1.8	0.45	0.52	1.4
	2.2	0.53	0.54	1.6
	2.3	0.49	0.54	1.5
Polycrystalline Alumina-III	1.0	0.38	0.47	1.2
	1.6	0.45	0.41	1.3
	1.9	0.47	0.60	1.5
	2.3	0.55	0.62	1.7
	2.3	0.51	0.56	1.6
Synthetic Sapphire	1.1	0.47	0.45	1.4
	1.3	0.47	0.47	1.4
	1.8	0.49	0.53	1.5
	2.1	0.47	0.70	1.6
	2.3	0.47	0.66	1.6
	2.3	0.45	0.70	1.6
Single Crystal MgO	1.2	0.34	0.46	1.1
	1.7	0.40	0.43	1.2
	2.2	0.43	0.43	1.3
	2.3	-	0.32	-
Transparent Polycrystalline Y ₂ O ₃	1.0	0.11	0.09	0.3
	1.2	-	0.11	-
	1.7	0.11	0.15	0.4
	2.1	0.09	0.15	0.3
	2.3	0.13	0.11	0.4
	2.3	0.17	0.11	0.5

^aTypes of polycrystalline alumina are as follows: I, Coors AD-995; II, Wesgo AL-995; III, GE Opaque Lucalox.

Table 10. Comparison of the Volume Expansion of Polycrystalline Alumina and Four Other Electrical Insulators Irradiated in the EBR-II (0-4)

Types of Specimen	Design Temp. (°C)	Fast Fluence (n/cm ² , > 1 MeV)	Diameter Increase (%)	Length Increase (%)	Volume Increase (%)
		x 10 ²¹			
GE Opaque Lucalox (polycrystalline)	400	0.6	0.67	0.62	2.0
	400	0.7	0.69	0.64	2.0
	400	0.7	0.67	0.70	2.0
	800	0.6	0.91	0.91	2.7
	800	0.8	0.96	1.00	2.9
	800	0.7	0.93	0.93	2.8
Synthetic sapphire	400	0.6	0.48	0.83	1.8
	400	0.6	0.56	0.93	2.1
	400	0.7	0.53	1.00	2.1
	800	0.8	0.32	0.69	1.3
	800	0.7	0.11	2.40	2.6
	800	0.6	0.19	2.17	2.6
Single-crystal MgO	800	0.7	0.08	0.05	0.2
	800	0.5	0.05	0.03	0.1
	800	0.4	0.03	0.05	0.1
Transparent poly- crystalline Y ₂ O ₃	400	0.6	0.19	0.19	0.6
	400	0.6	0.16	0.13	0.5
	400	0.7	0.16	0.11	0.4
	800	0.8	0.11	0.00	0.2
	800	0.6	0.08	0.08	0.2
	800	0.5	0.08	0.08	0.2
Silicon oxynitride (Si ₂ ON ₂)	400	0.5	-0.16	-	-
	400	0.6	-0.13	-0.08	-0.34
	400	0.7	-0.03	-0.05	-0.11
	800	0.8	-0.08	-0.03	-0.19
	800	0.8	-0.05	-0.05	-0.15
	800	0.7	-0.03	-0.03	-0.09
	800	0.5	0.00	-0.05	-0.05

DISCUSSION AND CONCLUSIONS

Exposure of polycrystalline alumina to fast neutrons can cause gross fracturing, an increase in volume as a result of swelling of the grains, and separation at the grain boundaries, which adds to the increase in volume. The degree of damage, as judged by the extent of these manifestations, depends strongly on the irradiation temperature, the purity of the alumina, and the average grain size.

Gross fracturing is related mainly to the impurity content of alumina, but it is also affected by the irradiation temperature. Gross fractures were virtually absent in specimens irradiated to fast fluences up to 5×10^{21} neutrons/cm² at temperatures below 100°C. Some specimens fractured, however, in assemblies irradiated at higher temperatures (580 to 1070°C). The specimens in the latter assemblies received fast fluences ranging from 1 to 6×10^{21} neutrons/cm², but fracturing could not be correlated with the fast fluence. Fracturing also did not appear to correlate with the temperature over the range 580 to 1070°C or with the grain size of the specimens. Specimens of high purity sustained fewer fractures, however, than the specimens of lesser purity.

The irradiation temperature affects the expansion in volume of individual grains and also separation at the grain boundaries, which is a result of this expansion. The effect of temperature was found to be quite complex; five stages, each of which gradually blends into each succeeding stage, were recognized from the data. These stages are:

1. Below 100°C - Neutron damage is minimal for alumina of all four types. There is a gradual increase in volume with increasing fast fluence.
2. 100 to 600°C - There is an increase in damage with increasing temperature. This effect is especially pronounced with large-grained alumina, which undergoes separation at the grain boundaries upon receiving high fast fluences.
3. 600 to 1070°C - The irradiation temperature has little effect on damage over this range. Damage increases in severity with increasing fast fluence.

4. Approximately 1100°C and above - Neutron damage is substantially less than in stage (3) above.
5. Approximately 1200°C and above - Neutron damage is much worse than in stage (3) above. Severe separation at the grain boundaries, especially in large-grain alumina, takes place and causes a large expansion in volume. Some specimens fractured.

The complex behavior of alumina with respect to the irradiation temperature may be explained by reference to the data of Wilks, et al.⁹ who directly measured the dimensions of single crystals irradiated at 150°C and 650°C. The expansion in volume of the crystal irradiated at 150°C (see Fig. 2) is consistent with the data for polycrystalline alumina irradiated at 70-90°C. The a and c parameters expanded by about the same percentage. The crystal irradiated at 650°C (see Fig. 5), however, increased in volume by a greater amount; the increase in volume is consistent with the greater expansion observed at higher temperatures (580 to 1070°C) for polycrystalline specimens in which separation at the grain boundaries did not occur. The increase in volume was anisotropic at 650°C. The c parameter expanded much more than the a parameter percentage-wise. The anisotropic expansion of the randomly oriented grains would produce stresses on the grain boundaries and may ultimately cause them to separate. This effect can account for the grain-boundary separation observed in the high temperature irradiations. As would be expected, the effect was more pronounced in large-grained alumina. The transition from isotropic to anisotropic expansion of the grains is apparently complete at a temperature of approximately 600°C; higher irradiation temperatures do not seem to intensify this effect significantly.

Lattice parameter changes of aluminum oxide at high temperature (over the range 600 to 1070°C) are very small. Almost all of the crystal expansion must, therefore, result from clusters of defects that are too large to affect the measured lattice parameters. An increase in temperature from 100°C to about 600°C may cause a thermal expansion of the lattice in a manner that would permit preferential lodging of defect clusters between basal planes. This could explain the conversion from isotropic to anisotropic expansion over this temperature range.

The rate of in-reactor thermal annealing of defects produced by fast neutrons becomes rapid enough at about 1100°C so that damage is substantially reduced. Some other effects must become predominant at still higher temperatures (approximately 1230°C) to again greatly increase the severity of damage. Separation at the grain boundaries is especially severe at very high temperatures. One possible explanation is that the effect of thermal cycling during irradiation at temperatures substantially greater than 1100°C results in more severe separation at grain boundaries than at lower temperatures. Comparisons of results for specimens irradiated to comparable fluences in the long-term assembly 41-39 and the short-term assembly 41-38 indicate that thermal cycling is a factor in producing damage even in the lower temperature range 600 to 1070°C. It should be emphasized, however, that thermal cycling does not in itself cause separation at the grain boundaries, but it may promote such separation of grain boundaries that are under stress because of anisotropic expansion.

The operating temperatures of practical nuclear-powered thermionic converters would be expected to lie within the range 500 to 1100°C. Based on the results shown in Figs. 5 and 6 for this temperature range, the following recommendations and conclusions can be made for the use of polycrystalline alumina as electrical insulators in such devices:

1. The alumina should be of high purity and small grain size to minimize gross fracturing and separation at grain boundaries.
2. The device should not be thermally cycled unnecessarily. There is evidence (see Fig. 6) that thermal cycling promotes separation at grain boundaries in irradiated alumina.
3. In a neutron energy spectra like that in the ETR core, electrical insulators made from alumina of high purity and small grain size will be able to withstand fast fluences up to about 3×10^{21} neutrons/cm² for energies greater than 1 MeV as calculated in the manner given in the Experimental Section. The design should allow for an increase in volume of about 3%.
4. In a neutron energy spectra like that in the EBR-II core, which has a greater number of neutrons that can cause displacements within the energy range below 1 MeV, the maximum fluence is probably no more than 2×10^{21} neutrons/cm² for neutrons with energies greater than 1 MeV.

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APPENDICES

APPENDIX A

TABULATED DATA FOR IRRADIATED ALUMINA

The materials listed are as follows:

I, Coors AD-995

II, Wesgo AL-995

III, GE Opaque Lucalox

IV, GE Translucent Lucalox.

Under the columns headed Results of Metallographic Examinations,

G = grain boundary separation is present, and N = grain-boundary separation is absent.

Volume increase of the cylindrical specimens was calculated using the equation

$$\Delta V/V = 2\Delta D/D + \Delta L/L,$$

in which V = volume, D = diameter, and L = length. The volume increase of the cylindrical shells was calculated using the same equation, but the outside diameter of the shells was used for D because measurements of the wall thickness were not precise enough for volume calculations.

Dimensional data for some of the thin-walled cylindrical shells are not tabulated because the specimens broke during hot cell disassembly of the capsules.

ASSEMBLY 41-23

Capsule Number	Specimen Number	Material	Fast Neutron Fluence (n/cm ² , > 1 MeV) x 10 ²¹	Irrad. Temp. (°C)	Pre-Irrad. Length (in.)	Post-Irrad. Length (in.)	Length Increase (%)	Pre-Irrad. Diameter (in.)	Post-Irrad. Diameter (in.)	Diameter Increase (%)	Volume Increase (%)	Gross Damage
231	231-T	IV	1.3	110	0.5010	0.5030	0.40	0.5014	0.5042	0.56	1.5	
	231-2	IV	1.4	140	0.5022	0.5041	0.38	0.5029	0.5056	0.54	1.5	
	231-11	IV	2.9	250	0.4954	0.4979	0.50	0.5010	0.5047	0.74	2.0	
232	232-4	IV	4.2	295	0.5008	0.5052	0.88	0.5023	0.5082	1.17	3.2	Fractured
	232-6	IV	4.4	300	0.5010	0.5071	1.22	0.5019	-	-	-	Broken
	232-7	IV	4.5	310	0.5015	0.5078	1.25	0.5005	0.5080	1.50	4.2	Fractured
	232-9	IV	4.7	320	0.5019	0.5081	1.24	0.5028	0.5108	1.59	4.4	
	232-12	IV	4.9	325	0.5020	0.5097	1.53	0.5006	0.5095	1.78	5.1	Fractured
233	233-9	IV	5.2	280	0.4999	0.5084	1.70	0.5011	0.5104	1.86	5.4	Fractured
	233-11	IV	5.1	280	0.4975	0.5048	1.47	0.4999	0.5132	2.66	6.8	Fractured
234	234-2	IV	4.0	190	0.5010	0.5082	1.44	0.5011	0.5085	1.48	4.4	Fractured
	234-4	IV	3.7	160	0.5031	0.5084	1.05	0.5021	0.5083	1.23	3.5	Fractured
	234-6	IV	3.3	140	0.5010	0.5057	0.94	0.5023	0.5078	1.10	3.1	Fractured
	234-7	IV	3.0	110	0.5024	0.5059	0.70	0.5012	0.5052	0.80	2.3	Fractured

ASSEMBLY 41-24

Capsule Number	Specimen Number	Material	Fast Neutron Fluence (n/cm ² , > 1 MeV) x 10 ²¹	Irrad. Temp. (°C)	Pre-Irrad. Length (in.)	Post-Irrad. Length (in.)	Length Increase (%)	Pre-Irrad. Diameter (in.)	Post-Irrad. Diameter (in.)	Diameter Increase (%)	Volume Increase (%)	Gross Damage
241	241-1	IV	0.6	110	0.4998	0.5015	0.34	0.5026	0.5047	0.42	1.2	
	241-2	IV	0.7	120	0.5024	0.5051	0.54	0.5019	0.5041	0.44	1.4	
	241-4	IV	0.8	165	0.4986	0.5011	0.50	0.5007	0.5032	0.50	1.5	
	241-7	IV	1.0	190	0.5051	0.5071	0.40	0.5017	0.5036	0.38	1.2	
	241-14	IV	1.5	260	0.4995	0.5014	0.38	0.5011	0.5041	0.60	1.6	
	241-16	IV	1.7	270	0.5008	0.5030	0.44	0.4999	0.5029	0.60	1.6	
242	242-1	IV	1.9	280	0.5005	0.5026	0.42	0.5012	0.5044	0.64	1.7	
	242-9	IV	2.3	310	0.5009	0.5042	0.66	0.5008	0.5040	0.64	1.9	
	242-11	IV	2.4	320	0.5015	0.5053	0.76	0.5013	0.5048	0.70	2.2	
	242-14	IV	2.5	325	0.5032	0.5073	0.82	0.5018	0.5049	0.62	2.1	Fractured
	242-16	IV	2.6	325	0.5005	0.5056	1.02	0.5017	0.5054	0.74	2.5	
243	243-1	IV	2.7	325	0.5009	0.5055	0.92	0.5024	0.5071	0.94	2.8	
	243-12	IV	2.7	280	0.5017	0.5063	0.92	0.5014	0.5048	0.68	2.3	Fractured
	243-15	IV	2.6	250	0.5027	0.5059	0.64	0.5010	0.5045	0.70	2.0	Fractured
	243-16	IV	2.6	240	0.4994	0.5034	0.80	0.5009	0.5046	0.74	2.3	Fractured
244	244-6	IV	1.9	150	0.5019	0.5047	0.56	0.5017	0.5048	0.62	1.8	
	244-8	IV	1.7	120	0.4987	0.5017	0.60	0.5006	0.5037	0.62	1.8	
	244-10	IV	1.5	110	0.5025	0.5053	0.56	0.5015	0.5042	0.54	1.6	
	244-16	IV	0.9	< 100	0.5023	0.5047	0.48	0.5025	0.5047	0.44	1.4	

ASSEMBLY 41-37

Capsule Number	Specimen Number	Material	Fast Neutron Fluence (n/cm ² , > 1 MeV) x 10 ²¹	Irrad. Temp. (°C)	Pre-Irrad. Length (in.)	Post-Irrad. Length (in.)	Length Increase (%)	Pre-Irrad. Diameter (in.)	Post-Irrad. Diameter (in.)	Diameter Increase (%)	Volume Increase (%)	Gross Damage	Results of Metallographic Examinations
371	371-3	IV	1.8	68	0.4868	0.4892	0.49	0.4994	0.5020	0.52	1.5		N
	371-4	IV	1.9	70	0.4870	0.4895	0.51	0.4994	0.5021	0.54	1.6		
372	372-3	IV	3.6	78	0.4866	0.4895	0.60	0.4993	0.5025	0.64	1.9		
	372-4	IV	3.7	80	0.4862	0.4892	0.62	0.4994	0.5027	0.66	1.9		
373	373-3	IV	5.3	88	0.4868	0.4904	0.74	0.4993	0.5031	0.76	2.3		
	373-4	IV	5.4	91	0.4870	0.4903	0.68	0.4993	0.5030	0.74	2.2		
374	374-3	IV	5.5	91	0.4867	0.4904	0.76	0.4993	0.5034	0.82	2.4		N
	374-4	IV	5.4	90	0.4871	0.4906	0.72	0.4993	0.5032	0.78	2.3		
375	375-3	IV	4.6	86	0.4871	0.4904	0.68	0.4993	0.5032	0.78	2.2	Chipped	
	375-4	IV	4.5	83	0.4866	-	-	0.4993	-	-	-	Broken	
376	376-3	IV	2.6	71	0.4871	0.4902	0.64	0.4992	0.5027	0.70	2.0		
	376-4	IV	2.5	68	0.4869	0.4899	0.62	0.4993	0.5025	0.64	1.9		

ASSEMBLY 41-44

Capsule Number	Specimen Number	Material	Fast Neutron Fluence (n/cm ² , > 1 MeV) x 10 ²¹	Irrad. Temp. (°C)	Pre-Irrad. Length (in.)	Post-Irrad. Length (in.)	Length Increase (%)	Pre-Irrad. Diameter (in.)	Post-Irrad. Diameter (in.)	Diameter Increase (%)	Volume Increase (%)	Gross Damage
441	441-6	IV	0.2	60-90	0.4681	0.4697	0.34	0.4700	0.4713	0.28	0.9	None
	441-7	III	0.2		0.4638	0.4652	0.30	0.4700	0.4712	0.26	0.8	
	441-8	I	0.2		0.4622	0.4638	0.35	0.4699	0.4713	0.30	1.0	
	441-14	IV	0.3		0.4651	0.4667	0.34	0.4700	0.4715	0.32	1.0	
	441-15	III	0.3		0.4634	0.4654	0.43	0.4700	0.4715	0.32	1.1	
	441-16	II	0.4		0.4636	0.4654	0.39	0.4700	0.4715	0.32	1.0	
	441-17	I	0.4		0.4688	0.4705	0.36	0.4699	0.4714	0.32	1.0	
442	442-11	I	0.7		0.4689	0.4709	0.43	0.4696	0.4715	0.32	1.0	
	442-12	IV	0.7		0.4643	0.4657	0.30	0.4700	0.4718	0.41	1.3	
	442-13	III	0.7		0.4644	0.4766	0.47	0.4700	0.4718	0.38	1.1	
	442-14	II	0.7		0.4611	0.4622	0.24	0.4700	0.4717	0.38	1.2	
	442-15	III	0.7		0.4660	0.4681	0.45	0.4700	0.4718	0.36	1.0	
	442-16	IV	0.7		0.4657	0.4675	0.39	0.4700	0.4718	0.38	1.2	
	442-17	II	0.7		0.4640	0.4658	0.39	0.4700	0.4718	0.38	1.2	
443	443-1	III	0.7		0.4655	0.4672	0.36	0.4700	0.4718	0.38	1.2	
	443-2	III	0.7		0.4661	0.4678	0.37	0.4700	0.4718	0.38	1.1	
	443-13	IV	0.7		0.4681	0.4700	0.41	0.4700	0.4719	0.38	1.1	
	443-14	III	0.7		0.4655	0.4673	0.39	0.4700	0.4718	0.40	1.2	
	443-15	II	0.6		0.4671	0.4690	0.41	0.4700	0.4718	0.38	1.2	
	443-16	I	0.6		0.4674	0.4695	0.45	0.4699	0.4717	0.38	1.2	
	443-17	IV	0.6		0.4650	0.4671	0.45	0.4700	0.4719	0.38	1.2	
444	444-6	IV	0.4		0.4675	0.4691	0.34	0.4700	0.4715	0.40	1.3	
	444-7	II	0.4		0.4682	0.4701	0.41	0.4700	0.4715	0.32	1.0	
	444-8	III	0.4		0.4650	0.4665	0.32	0.4700	0.4715	0.32	1.1	
	444-9	I	0.4		0.4682	0.4698	0.34	0.4699	0.4711	0.32	1.0	
	444-15	II	0.3		0.4676	0.4691	0.32	0.4700	0.4713	0.26	0.9	
	444-16	I	0.3		0.4697	0.4712	0.32	0.4697	0.4710	0.28	0.9	
	444-17	III	0.3		0.4657	0.4671	0.30	0.4700	0.4711	0.28	0.9	
										0.23	0.8	

ASSEMBLY 41-46

Capsule Number	Specimen Number	Material	Fast Neutron Fluence (n/cm ² , > 1 MeV) x 10 ²¹	Irrad. Temp. (°C)	Pre-Irrad. Length (in.)	Post-Irrad. Length (in.)	Length Increase (%)	Pre-Irrad. Diameter (in.)	Post-Irrad. Diameter (in.)	Diameter Increase (%)	Volume Increase (%)	Gross Damage
361	461-6	IV	0.9	60-90	0.4661	0.4683	0.47	0.4699	0.4720	0.45	1.4	None ↓
	461-7	III	1.0		0.4658	0.4680	0.47	0.4699	0.4720	0.45	1.4	
	461-8	I	1.0		0.4681	0.4695	0.30	0.4699	0.4719	0.43	1.2	
	461-14	III	1.5		0.4643	0.4665	0.47	0.4699	0.4721	0.47	1.4	
	461-15	II	1.6		0.4628	0.4657	0.63	0.4699	0.4721	0.47	1.6	
	461-16	I	1.7		0.4590	0.4612	0.48	0.4698	0.4722	0.51	1.5	
462	462-11	I	2.7		0.4644	0.4668	0.47	0.4698	0.4725	0.58	1.6	
	462-12	IV	2.8		0.4685	0.4713	0.60	0.4699	0.4726	0.57	1.7	
	462-13	III	2.8		0.4645	0.4673	0.60	0.4699	0.4725	0.54	1.7	
	462-14	II	2.9		0.4659	0.4689	0.64	0.4699	0.4725	0.55	1.7	
	462-15	III	2.9		0.4640	0.4669	0.62	0.4699	0.4726	0.57	1.8	
	462-16	II	2.9		0.4676	0.4705	0.62	0.4699	0.4725	0.55	1.7	
463	463-1	III	3.0		0.4652	0.4680	0.60	0.4699	0.4725	0.55	1.7	
	463-2	I	3.0		0.4627	0.4657	0.65	0.4698	0.4724	0.55	1.8	
	463-13	IV	2.7		0.4676	0.4702	0.56	0.4699	0.4728	0.62	1.8	
	463-14	III	2.6		0.4636	0.4662	0.56	0.4699	0.4727	0.60	1.8	
	463-15	II	2.6		0.4640	0.4671	0.67	0.4699	0.4728	0.62	1.9	
	463-16	I	2.5		0.4655	0.4689	0.73	0.4697	0.4726	0.62	2.0	
464	464-6	IV	2.0		0.4663	0.4690	0.71	0.4699	0.4722	0.49	1.7	
	464-7	II	1.9		0.4678	0.4703	0.53	0.4699	0.4723	0.51	1.6	
	464-8	III	1.8		0.4663	0.4688	0.54	0.4699	0.4722	0.49	1.5	
	464-9	I	1.8		0.4650	0.4674	0.52	0.4698	0.4721	0.49	1.5	
	464-15	II	1.3		0.4643	0.4667	0.52	0.4699	0.4719	0.43	1.4	
	464-16	III	1.2		0.4649	0.4673	0.52	0.4699	0.4720	0.45	1.4	

ASSEMBLY 41-38 (SOLID CYLINDERS)

Capsule Number	Specimen Number	Material	Fast Neutron Fluence (n/cm ² , > 1 MeV) x 10 ²¹	Irrad. Temp. (°C)	Pre-Irrad. Length (in.)	Post-Irrad. Length (in.)	Length Increase (%)	Pre-Irrad. Diameter (in.)	Post-Irrad. Diameter (in.)	Diameter Increase (%)	Volume Increase (%)	Gross Damage	Results of Metallographic Examinations
1	38-1	IV	0.4	400	0.4772	0.4797	0.52	0.4934	0.4946	0.28	1.1		
	38-2	II	0.45	400	0.4731	0.4747	0.34	0.4939	0.4947	0.16	0.7		
	38-3	III	0.5	400	0.4751	0.4769	0.38	0.4937	0.4950	0.26	0.9		
	38-4	I	0.6	400	0.4738	0.4762	0.51	0.4931	0.4946	0.26	1.0		
3	38-8	IV	1.0	710	0.4771	0.4815	0.92	0.4933	0.4969	0.72	2.4		
	38-9	II	1.1	710	0.4756	0.4783	0.57	0.4936	0.4959	0.47	1.5		
	38-10	III	1.2	710	0.4740	0.4786	0.97	0.4936	0.4965	0.59	2.2		
	38-11	I	1.3	710	0.4733	0.4763	0.63	0.4939	0.4975	0.73	2.1		
4	38-12	IV	1.4	1070	0.4772	0.4826	1.13	0.4931	0.4979	0.97	3.1		N
	38-13	II	1.5	1070	0.4758	0.4789	0.65	0.4932	0.4958	0.53	1.7		N
	38-14	III	1.6	1070	0.4746	0.4786	0.84	0.4936	0.4971	0.71	2.3		N
	38-15	I	1.7	1070	0.4731	0.4787	1.18	0.4934	0.4988	1.09	3.4	Small crack	
5	38-16	IV	1.75	750	0.4772	0.4829	1.19	0.4934	0.4982	0.97	3.1		N
	38-17	III	1.85	750	0.4746	0.4785	0.82	0.4939	0.4973	0.69	2.2		N
	38-18	II	1.95	750	0.4738	0.4776	0.80	0.4937	0.4974	0.74	2.3	Very thin crack	N
6	38-19	II	2.05	630	0.4746	0.4785	0.82	0.4937	0.4978	0.83	2.5		
	38-20	III	2.15	630	0.4739	0.4782	0.91	0.4936	0.4973	0.75	2.4		
	38-21	I	2.25	630	0.4743	0.4776	0.70	0.4936	0.4985	0.99	2.7	Small crack	
7	38-22	IV	2.35	580	0.4770	0.4844	1.55	0.4922	0.4991	1.18	3.9		G
	38-23	II	2.4	580	0.4780	0.4825	0.94	0.4940	0.4988	0.97	2.9	Crack	G
	38-24	III	2.5	580	0.4752	0.4801	1.03	0.4932	0.4978	0.93	2.9		N
	38-28	II	2.8	790	0.4780	0.4857	1.61	0.4936	0.5002	1.33	4.3		
	38-29	III	2.85	790	0.4755	0.4801	0.97	0.4932	0.4980	0.97	2.9		N
	38-30	I	2.9	790	0.4729	0.4773	0.93	0.4941	0.5015	1.50	3.9		
9	38-34	IV	3.1	1100	0.4771	0.4785	0.50	0.4932	0.4953	0.43	1.4		N
	38-35	II	3.1	1100	0.4779	0.4793	0.29	0.4938	-	-	0.9	Broken in half	
	38-36	III	3.1	1100	0.4746	0.4767	0.44	0.4934	0.4956	0.45	1.3		N
	38-37	I	3.1	1100	0.4736	0.4757	0.44	0.4939	-	-	1.3	Broken in half	
11	38-41	II	2.95	930	0.4745	0.4832	1.83	0.4937	0.5019	1.66	5.2		G
	38-42	III	2.9	930	0.4742	0.4793	1.08	0.4934	0.4981	0.95	3.0		
	38-43	I	2.8	930	0.4739	0.4793	1.14	0.4934	0.5013	1.60	4.3	Large crack	
12	38-47	II	2.4	1230	0.4747	0.4852	2.21	0.4938	0.5036	1.98	6.2		G
	38-48	III	2.35	1230	0.4743	0.4784	0.86	0.4933	0.4978	0.91	2.7		
	38-49	I	2.25	1230	0.4720	0.4780	1.27	0.4931	0.5048	2.37	6.0	Large cracks	
13	38-53	II	1.8	910	0.4772	0.4814	0.88	0.4933	0.4981	0.97	2.8	Very thin crack	
	38-54	III	1.7	910	0.4750	0.4786	0.76	0.4929	0.4964	0.71	2.2		N
	38-55	I	1.65	910	0.4733	0.4768	0.74	0.4938	0.4973	0.70	2.1	Very thin crack	

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ASSEMBLY 41-38 (CYLINDRICAL SHELLS)

Capsule Number	Specimen Number	Material	Fast Neutron Fluence (n/cm ² , > 1 MeV) x 10 ²¹	Irrad. Temp. (°C)	Pre-Irrad. Length (in.)	Post-Irrad. Length (in.)	Length Increase (%)	Pre-Irrad. Diameter (in.)		Post-Irrad. Diameter (in.)		Diameter Increase (%)	Volume Increase (%)	Gross Damage
								OD	ID	OD	ID			
2	38-5	II	0.7	430										Broken
	38-6	III	0.8	430	0.4711	0.4717	0.1	0.4941	0.4540	0.4970	0.4560	0.5	1.1	Broken
	38-7	I	0.9	430		-				-	-			
7	38-25	II	2.7	550	0.4778	0.4827	1.0	0.4928	0.4545	0.4977	0.4592	1.0	3.0	
	38-26	III	2.9	550	0.4690	0.4746	1.2	0.4941	0.4532	0.4999	0.4590	1.2	3.6	
	38-27	I	3.0	500	0.4768	0.4814	1.0	0.4937	0.4536	0.4999	0.4594	1.3	3.6	
8	38-31	II	3.1	790		-				-	-			-
	38-32	III	3.2	790		-				-	-			-
	38-33	I	3.2	790		-				-	-			
10	38-38	II	3.2	1200	0.4793	0.4946				-	-			
	38-39	III	3.1	1200	0.4667	0.4681	0.3	0.4936	0.4536	0.4977	0.4575	0.8	1.9	-
	38-40	I	3.0	1200	-	-				-	-			-
11	38-44	II	2.7	930		0.4824				-	-			Cracked
	38-45	III	2.5	930	-					-	-			Broken
	38-46	I	2.4	930	-					-	-			Broken
12	38-50	II	1.7	1230	-					-	-			Broken
	38-51	III	1.5	1230	-					-	-			Broken
	38-52	I	1.3	1230	-					-	-			Broken
13	38-56	II	0.8	910	-					-	-			Broken
	38-57	III	0.7	910	-					-	-			Broken
	38-58	I	0.6	910	-					-	-			Broken

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ASSEMBLY 41-39 (SOLID CYLINDERS)

Capsule Number	Specimen Number	Material	Fast Neutron Fluence (n/cm ² , > 1 MeV) x 10 ²¹	Irrad. Temp. (°C)	Pre-Irrad. Length (in.)	Post-Irrad. Length (in.)	Length Increase (%)	Pre-Irrad. Diameter (in.)	Post-Irrad. Diameter (in.)	Diameter Increase (%)	Volume Increase (%)	Gross Damage	Results of Metallographic Examinations
1	39-1	IV	1.0	400	0.4762	0.4802	0.84	0.4931	0.4960	0.59	2.0		
	39-2	II	1.1	400	0.4752	0.4774	0.46	0.4931	0.4959	0.57	1.6		
	39-3	III	1.2	400	0.4753	0.4785	0.67	0.4929	0.4959	0.61	1.9		
	39-4	I	1.3	400	0.4740	0.4766	0.55	0.4931	0.4962	0.63	1.8		
3	39-8	IV	2.1	710	0.4760	0.4841	1.70	0.4930	0.5004	1.50	4.7		
	39-9	II	2.2	710	0.4747	0.4806	1.18	0.4932	0.4994	1.26	3.7		
	39-10	III	2.4	710	0.4747	0.4808	1.28	0.4930	0.4998	1.38	4.0		
	39-11	I	2.5	710	0.4746	0.4786	0.84	0.4932	0.5012	1.62	4.1	Crack	
4	39-12	IV	2.7	1070	0.4760	0.4853	1.95	0.4931	0.5013	1.66	5.3		
	39-13	II	2.9	1070	0.4748	0.4810	1.30	0.4932	0.5008	1.54	4.4		
	39-14	III	3.1	1070	0.4750	0.4819	1.45	0.4931	0.5000	1.40	4.3		N
	39-15	I	3.3	1070	0.4745	0.4817	1.52	0.4931	0.5010	1.60	4.7	Crack	
5	39-16	IV	3.5	750	0.4760	0.4878	2.48	0.4931	0.5038	2.17	6.8		
	39-17	III	3.7	750	0.4748	0.4827	1.66	0.4932	0.5019	1.77	5.2		G (some)
	39-18	II	3.9	750	0.4746	0.4859	2.38	0.4933	0.5056	2.50	7.4		
6	39-19	II	4.1	630	0.4745	0.4817	1.51	0.4931	0.5010	1.60	4.7	Crack	
	39-20	III	4.2	630	0.4741	0.4807	1.39	0.4931	0.5008	1.56	4.5		N
	39-21	I	4.4	630	0.4742	0.4800	1.22	0.4931	0.5025	1.91	5.0	Crack	
7	39-22	IV	4.5	580	0.4748	0.4863	2.42	0.4930	0.5031	2.04	6.5		
	39-23	II	4.7	580	0.4753	0.4852	2.08	0.4932	0.5018	1.74	5.6		G
	39-24	III	5.0	580	0.4747	0.4827	1.69	0.4931	0.5062	2.66	7.0		
8	39-28	II	5.4	790	0.4751	0.4892	2.97	0.4932	0.5062	2.64	8.3		
	39-29	III	5.5	790	0.4746	0.4818	1.52	0.4932	-	-	4.6	Broken-three pieces	
	39-30	I	5.5	790	0.4745	0.4819	1.56	0.4931	0.5054	2.50	6.6		
9	39-34	IV	5.8	1100	0.4760	0.4812	1.09	0.4931	-	-	3.3	Split in half	
	39-35	II	5.8	1100	0.4744	0.4810	1.39	0.4932	0.5005	1.48	4.4		G
	39-36	III	5.7	1100	0.4746	0.4785	0.82	0.4932	0.4978	0.93	2.7		N
	39-37	I	5.6	1100	0.4745	0.4783	0.80	0.4932	-	-	2.4	Split in half	
11	39-41	II	5.2	930	0.4746	0.4891	3.06	0.4933	0.5082	3.02	9.1		
	39-42	III	5.0	930	0.4741	0.4800	1.25	0.4932	0.5007	1.92	5.1	Chipped	
	39-43	I	4.9	930	0.4739	0.4805	1.39	0.4931	0.5052	2.45	6.3		
12	39-47	II	4.0	1230	0.4745	0.4853	2.28	0.4931	-	-	6.8	Split in half	
	39-48	III	3.8	1230	0.4748	0.4797	1.03	0.4931	-	-	3.1	Split in half	
	39-49	I	3.6	1230	0.4745	0.4807	1.31	0.4932	0.5047	2.33	6.0	Crack	
13	39-53	II	2.5	910	0.4748	0.4853	2.21	0.4932	0.5038	2.15	6.5	Crack	
	39-54	III	2.3	910	0.4744	0.4794	1.05	0.4931	0.4994	1.28	3.6		G (some)
	39-55	I	2.0	910	0.4744	0.4786	0.89	0.4933	0.5008	1.52	3.9	Crack	

ASSEMBLY 41-39 (CYLINDRICAL SHELLS)

Capsule Number	Specimen Number	Material	Fast Neutron Fluence (n/cm ² , > 1 MeV) x 10 ²¹	Irrad. Temp. (°C)	Pre-Irrad. Length (in.)	Post-Irrad. Length (in.)	Length Increase (%)	Pre-Irrad. Diameter		Post-Irrad. Diameter		Diameter Increase (%)	Volume Increase (%)	Gross Damage
								OD	ID	OD	ID			
2	39-5	II	1.5	430										
	39-6	III	1.7	430										
	39-7	I	1.8	430										
7	39-25	II	5.1	550										
	39-26	III	5.2	550										Broken
	39-27	I	5.3	550										Broken
8	38-31	II	5.6	790										Broken
	39-32	III	5.7	790										Broken
	39-33	I	5.8	790										Broken
10	39-38	II	5.5	1200										Broken
	39-39	III	5.4	1200										Broken
	39-40	I	5.3	1200										Broken
11	39-44	II	4.7	930										Broken
	39-45	III	4.5	930										Broken
	39-46	I	4.3	930										Broken
12	39-50	II	3.4	1230										
	39-51	III	3.0	1230										Broken
	39-52	I	2.8	1230										Broken
13	39-56	II	1.8	910										
	39-57	III	1.6	910										
	39-58	I	1.4	910										

No post-irradiation measurements for any of the shells in this assembly.

ASSEMBLY 0-1 (SOLID CYLINDERS)

Capsule Number	Specimen Number	Material	Fast Neutron Fluence (n/cm ² , > 1 MeV) x 10 ²¹	Irrad. Temp. (°C)	Pre-Irrad. Length (in.)	Post-Irrad. Length (in.)	Length Increase (%)	Pre-Irrad. Diameter (in.)	Post-Irrad. Diameter (in.)	Diameter Increase (%)	Volume Increase (%)	Gross Damage	Results of Metallographic Examinations
1-1	C-114	I	0.6	690	0.3996	0.4019	0.58	0.4000	0.4022	0.55	1.7		
	W-115	II	0.7	690	0.3973	0.4002	0.72	0.4002	0.4027	0.62	2.0		
	O-116	III	0.7	690	0.3980	0.4011	0.78	0.3998	0.4025	0.68	2.1		N
1-2	C-124	I	1.1	730	0.3984	0.4017	0.83	0.3998	0.4040	1.05	2.9	Crack	
	W-125	II	1.1	730	0.3975	0.4033	1.46	0.4001	0.4058	1.43	4.3		
	O-126	III	1.2	730	0.3948	0.3985	0.93	0.4000	0.4035	0.87	2.7		
1-3	C-134	I	1.3	750	0.3981	0.4022	1.03	0.4000	0.4061	1.52	4.1	Crack	G (some)
	W-135	II	1.3	750	0.3975	0.4045	1.76	0.3997	0.4066	1.73	5.2		G (severe)
	O-136	III	1.3	750	0.3964	0.4001	0.93	0.4000	0.4038	0.95	2.8		N
1-4	C-144	I	1.2	730	0.3983	0.4019	0.91	0.3997	0.4047	1.25	3.4	Crack	
	W-145	II	1.2	730	0.3977	0.4034	1.44	0.3999	0.4058	1.47	4.4		
	O-146	III	1.1	730	0.3980	0.4016	0.91	0.3995	0.4029	0.85	2.6		N
1-5	C-154	I	1.0	690	0.3987	0.4008	0.52	0.3999	0.4020	0.53	1.6		
	W-155	II	0.9	690	0.3975	0.3996	0.53	0.3999	0.4020	0.53	1.6		
	O-156	III	0.9	690	0.3971	0.3993	0.56	0.4000	0.4022	0.55	1.7		

ASSEMBLY 0-1 (CYLINDRICAL SHELLS)

Capsule Number	Specimen Number	Material	Fast Neutron Fluence (n/cm ² , > 1 MeV) x 10 ²¹	Irrad. Temp. (°C)	Pre-Irrad. Length (in.)	Post-Irrad. Length (in.)	Length Increase (%)	Pre-Irrad. Diameter (in.)		Post-Irrad. Diameter (in.)		Diameter Increase (%)		Volume Increase (%)	Gross Damage
								OD	ID	OD	ID	OD	ID		
1-1	CS-111	I	0.45	670	0.3974	0.3997	0.58	0.3999		0.4012		0.33		1.2	Crack
	WS-112	II	0.5	670	0.3972	0.3990	0.45	0.4000		0.4014		0.35		1.2	
	OS-113	III	0.6	670	0.3962	0.3989	0.68	0.3997		0.4017		0.50		1.7	
1-2	CS-121	I	0.9	710	0.3978	0.4003	0.63	0.3999		0.4027		0.70		2.0	
	WS-122	II	1.0	710	0.3975	0.4015	1.01	0.3998		0.4033		0.88		2.8	
	OS-123	III	1.1	710	0.3966	0.4013	1.19	0.3998		0.4029		0.78		2.8	
1-3	CS-131	I	1.2	750	0.3979	0.4012	0.83	0.4000		0.4040		1.00		2.8	
	WS-132	II	1.2	750	0.3951	0.4016	1.64	0.4002		0.4050		1.20		4.0	
	OS-133	III	1.2	750	0.3967	0.3998	0.78	0.4002		0.4038		0.87		2.5	
1-4	CS-141	I	1.2	740	0.3975	0.4007	0.81	0.4000		0.4039		0.98		2.8	
	WS-142	II	1.2	740	0.3980	0.4038	1.45	0.3995		0.4050		1.38		4.2	
	OS-143	III	1.2	740	0.3976	0.4007	0.78	0.4000		0.4032		0.80		2.4	
1-5	CS-151	I	1.1	710	0.3968	0.3990	0.56	0.4002		0.4029		0.67		1.9	
	WS-152	II	1.1	710	0.3958	0.3987	0.73	0.4001		0.4034		0.82		2.4	
	OS-153	III	1.0	710	0.3992	0.4019	0.68	0.3999		0.4025		0.65		2.0	

APPENDIX B

PHOTOMICROGRAPHS OF IRRADIATED ALUMINA

All photomicrographs are in the as-polished condition.

Type of Alumina:
Magnification:

I, Unirradiated
500X

Type of Alumina:
Magnification:

II, Unirradiated
500X

Type of Alumina:
Magnification:

III, Unirradiated
500X

Type of Alumina:
Magnification:

IV, Unirradiated
100X

Assembly No.:	41-37
Specimen No.:	371-3
Type of Alumina:	IV
Fast Fluence(n/cm ² , > 1 Mev):	1.8 x 10 ²¹
Irradiation Temp. (°C):	70
Magnification:	100X

Assembly No.: 41-37
Specimen No.: 371-3
Type of Alumina: IV
Fast Fluence, (n/cm², > 1 MeV): 1.8×10^{21}
Irradiation Temp. (°C): 70
Magnification: 500X

Assembly No.:	41-37
Specimen No.:	374-3
Type of Alumina:	IV
Fast Fluence(n/cm^2 , $> 1 \text{ MeV}$):	5.5×10^{21}
Irradiation Temp. ($^{\circ}\text{C}$)	90
Magnification:	100X

Assembly No.:	41-37
Specimen No.:	374-3
Type of Alumina:	IV
Fast Fluence(n/cm^2 , > 1 MeV):	5.5×10^{21}
Irradiation Temp. ($^{\circ}C$):	90
Magnification:	500X

Assembly No.:	41-37
Specimen No.:	374-3
Type of Alumina:	IV
Fast Fluence(n/cm ² , > 1 MeV):	5.5 x 10 ²¹
Irradiation Temp. (°C):	90
Magnification:	100X

Assembly No.:	41-37
Specimen No.:	374-3
Type of Alumina:	IV
Fast Fluence(n/cm^2 , > 1 MeV):	5.5×10^{21}
Irradiation Temp. ($^{\circ}C$):	90
Magnification:	500X

Assembly No.:	41-46
Specimen No.:	463-13
Type of Alumina:	IV
Fast Fluence(n/cm ² , > 1 Mev):	2.7 x 10 ²¹
Irradiation Temp. (°C):	90
Magnification:	100X

Assembly No.:	41-46
Specimen No.:	463-13
Type of Alumina:	IV
Fast Fluence(n/cm^2 , > 1 Mev):	2.7×10^{21}
Irradiation Temp. ($^{\circ}C$):	90
Magnification:	500X

Assembly No.:	41-38
Specimen No.:	38-12
Type of Alumina:	IV
Fast Fluence(n/cm^2 , > 1 MeV):	1.4×10^{21}
Irradiation Temp. ($^{\circ}C$):	1070
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-13
Type of Alumina:	II
Fast Fluence(n/cm^2 , > 1 MeV):	1.5×10^{21}
Irradiation Temp.($^{\circ}C$):	1070
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-14
Type of Alumina:	III
Fast Fluence(n/cm^2 , > 1 MeV):	1.6×10^{21}
Irradiation Temp.:	1070
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-15
Type of Alumina:	I
Fast Fluence(n/cm^2 , $> 1 \text{ MeV}$):	1.7×10^{21}
Irradiation Temp.($^{\circ}\text{C}$):	1070
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-16
Type of Alumina:	IV
Fast Fluence(n/cm^2 , $> 1 \text{ MeV}$):	1.75×10^{21}
Irradiation Temp. ($^{\circ}\text{C}$):	750
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-17
Type of Alumina:	III
Fast Fluence(n/cm ² , > 1 MeV):	1.85 x 10 ²¹
Irradiation Temp. (°C);	750
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-21
Type of Alumina:	I
Fast Fluence(n/cm^2 , > 1 MeV):	2.25×10^{21}
Irradiation Temp. ($^{\circ}\text{C}$):	630
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-21
Type of Alumina:	I
Fast Fluence(n/cm^2 , > 1 Mev):	2.25×10^{21}
Irradiation Temp.(°C):	630
Magnification:	500X

Assembly No.:	41-38
Specimen No.:	38-21
Type of Alumina:	I
Fast Fluence(n/cm^2 , > 1 MeV):	2.25×10^{21}
Irradiation Temp.(°C):	630
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-22
Type of Alumina:	IV
Fast Fluence(n/cm^2 , > 1 MeV):	2.35×10^{21}
Irradiation Temp. ($^{\circ}C$):	580
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-22
Type of Alumina:	IV
Fast Fluence(n/cm^2 , > 1 Mev):	2.35×10^{21}
Irradiation Temp.(°C):	580
Magnification:	500X

Assembly No.:	41-38
Specimen No.:	38-23
Type of Alumina:	II
Fast Fluence(n/cm ² , > 1 MeV):	2.4×10^{21}
Irradiation Temp. (°C):	580
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-23
Type of Alumina:	II
Fast Fluence(n/cm^2 , > 1 Mev):	2.4×10^{21}
Irradiation Temp. ($^{\circ}C$):	580
Magnification:	500X

Assembly No.:	41-38
Specimen No.:	38-24
Type of Alumina:	III
Fast Fluence(n/cm ² , > 1 MeV):	2.5 x 10 ²¹
Irradiation Temp. (°C):	580
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-24
Type of Alumina:	III
Fast Fluence(n/cm^2 , > 1 Mev):	2.5×10^{21}
Irradiation Temp. ($^{\circ}C$):	580
Magnification:	500X

Assembly No.:	41-38
Specimen No.:	38-29
Type of Alumina:	III
Fast Fluence(n/cm^2 , $> 1 \text{ MeV}$):	2.85×10^{21}
Irradiation Temp.($^{\circ}\text{C}$):	790
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-34
Type of Alumina:	IV
Fast Fluence(n/cm^2 , > 1 MeV):	3.1×10^{21}
Irradiation Temp.:	1100
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-36
Type of Alumina:	III
Fast Fluence (n/cm ² , > 1 MeV):	3.1 x 10 ²¹
Irradiation Temp. (°C):	1100
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-41
Type of Alumina:	II
Fast Fluence(n/cm ² , > 1 Mev):	2.95 x 10 ²¹
Irradiation Temp. (°C):	930
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-41
Type of Alumina:	II
Fast Fluence(n/cm^2 , > 1 Mev):	2.95×10^{21}
Irradiation Temp.(°C):	930
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-47
Type of Alumina:	II
Fast Fluence(n/cm^2 , $> 1 \text{ MeV}$):	2.4×10^{21}
Irradiation Temp. ($^{\circ}\text{C}$):	1230
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-54
Type of Alumina:	III
Fast Fluence(n/cm^2 , > 1 MeV):	1.7×10^{21}
Irradiation Temp. ($^{\circ}C$):	910
Magnification:	100X

Assembly No.:	41-38
Specimen No.:	38-54
Type of Alumina:	III
Fast Fluence(n/cm^2 , > 1 MeV):	1.7×10^{21}
Irradiation Temp.(°C):	910
Magnification:	500X

Assembly No.:	41-39
Specimen No.:	39-14
Type of Alumina:	III
Fast Fluence(n/cm ² , > 1 Mev):	3.1×10^{21}
Irradiation Temp.(°C):	1070
Magnification:	500X

Assembly No.:	41-39
Specimen No.:	39-17
Type of Alumina	III
Fast Fluence (n/cm ² , > 1 Mev):	3.7 x 10 ²¹
Irradiation Temp. (°C):	750
Magnification:	500X

Assembly No.:	41-39
Specimen No.:	39-20
Type of Alumina:	III
Fast Fluence(n/cm^2 , $> 1 \text{ Mev}$):	4.2×10^{21}
Irradiation Temp. ($^{\circ}\text{C}$):	630
Magnification:	500X

Assembly No.:	41-39
Specimen No.:	39-23
Type of Alumina:	II
Fast Fluence(n/cm^2 , > 1 Mev):	4.7×10^{21}
Irradiation Temp. ($^{\circ}C$):	580
Magnification:	100X

Assembly No.:	41-39
Specimen No.:	39-23
Type of Alumina:	II
Fast Fluence(n/cm ² , > 1 Mev):	4.7 x 10 ²¹
Irradiation Temp. (°C):	580
Magnification:	500X

Assembly No.:	41-39
Specimen No.:	39-35
Type of Alumina:	II
Fast Fluence(n/cm^2 , > 1 Mev):	5.8×10^{21}
Irradiation Temp.(°C):	1100
Magnification:	100X

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Assembly:	41-39
Specimen No.:	39-35
Type of Alumina:	II
Fast Fluence(n/cm^2 , > 1 Mev):	5.8×10^{21}
Irradiation Temp. ($^{\circ}C$):	1100
Magnification:	500X

Assembly No.:	41-39
Specimen No.:	39-36
Type of Alumina:	III
Fast Fluence(n/cm^2 , > 1 Mev):	5.7×10^{21}
Irradiation Temp.(°C):	1100
Magnification:	500X

Assembly No.:	41-39
Specimen No.:	39-54
Type of Alumina:	III
Fast Fluence(n/cm^2 , $> 1 \text{ Mev}$):	2.3×10^{21}
Irradiation Temp.($^{\circ}\text{C}$):	910
Magnification:	500X

Assembly No.:	0-1
Specimen No.:	116
Type of Alumina	III
Fast Fluence: (n/cm ² , > 1 Mev)	0.7 x 10 ²¹
Irradiation Temp. (°C):	690
Magnification:	100X

Assembly No.:	0-1
Specimen No.:	116
Type of Alumina:	III
Fast Fluence (n/cm^2 , $>1 \text{ Mev}$):	0.7×10^{21}
Irradiation Temp. ($^{\circ}\text{C}$)	690
Magnification:	500X

Assembly No.: 0-1
Specimen No.: 134
Type of Alumina: I
Fast Fluence (n/cm^2 , > 1 Mev): 1.3×10^{21}
Irradiation Temp. ($^{\circ}C$): 750
Magnification: 100X

Assembly No.:	0-1
Type of Alumina:	I
Specimen No.:	134
Fast Fluence(n/cm^2 , > 1 Mev):	1.3×10^{21}
Irradiation Temp. ($^{\circ}C$):	750
Magnification:	500X

Assembly No.:	0-1
Specimen No.:	135
Type of Alumina:	II
Fast Fluence (n/cm ² , >1 Mev):	1.3×10^{21}
Irradiation Temp. (°C):	750
Magnification:	100X

Assembly No.:	0-1
Specimen No.:	136
Type of Alumina:	III
Fast Fluence (n/cm ² , >1 Mev):	1.3×10^{21}
Irradiation Temp. (°C):	750
Magnification:	100X

Assembly No.:	0-1
Specimen No.:	136
Type of Alumina:	III
Fast Fluence (n/cm ² , >1 MeV):	1.3×10^{21}
Irradiation Temp. (°C):	750
Magnification:	500X

0.035 INCHES
100X

Assembly No.:	0-1
Specimen No.:	146
Type of Alumina:	III
Fast Fluence(n/cm^2 , > 1 Mev):	1.1×10^{21}
Irradiation Temp.(°C):	730
Magnification:	100X

Assembly No.:	0-1
Specimen No.:	146
Type of Alumina:	III
Fast Fluence(n/cm ² , > 1 Mev):	1.1 x 10 ²¹
Irradiation Temp. (°C):	730
Magnification:	500X

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